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Orthogonal optical labeling based on a 40 Gbit/s DPSK payload and a 2.5 Gbit/s IM label

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Abstract: We experimentally demonstrate label encoding/erasure and transmission for an orthogonally labeled signal using a 40 Gbit/s DPSK payload and an IM label. The influence of the modulation depth and the label erasure are discussed.

OCIS codes: (060.4250) Networks, (060.2360) Fiber optics links and subsystems

1. Introduction

Optical label controlled packet switching is a promising technique in future IP-over-WDM networks to forward packets in the optical layer independently of IP packet length and payload bit rate [1]. We have proposed a novel orthogonal optical labeling scheme using a return-to-zero differential phase-shift keying (RZ-DPSK) payload and a superimposed intensity modulated (IM) label [2], namely RZ-DPSK/IM labeling, and experimentally demonstrated label insertion/erasure and transmission for such a labeling scheme. Compared to traditional IM/DPSK labeling [3], RZ-DPSK/IM labeling will ease the laser linewidth requirement and allow building more stable integrated DPSK demodulators. Moreover, at 40 Gbit/s the RZ-DPSK modulation format has been shown to overcome nonlinear impairments and to extend transmission distance [4].

In this paper, we present our latest research on orthogonal optical labeling scheme consisting of a 40 Gbit/s DPSK payload and an IM label, as so called DPSK/IM labeling. We present, for the first time, an experimental investigation of label insertion, propagation over a 50 km dispersion compensated SMF transmission link and label erasure of an optically DPSK/IM labeled signal. The requirement on the modulation depth of the IM label and the influence from the label erasure are discussed. The scheme will take advantage of the more compact optical spectrum, robust dispersion and nonlinear tolerance during transmission [5] and, as already mentioned, alleviate laser linewidth requirements. Our results show that both RZ-DPSK/IM and DPSK/IM labeling could be a potential solution for future high speed optical label switching.

2. Orthogonal DPSK and IM modulation: theory

In the DPSK/IM labeling scheme, the payload is phase modulated while the label is intensity modulated on the same optical carrier. The electric field of the DPSK/IM signal can be expressed by $E(t)=\sqrt{P(t)}\exp\{j(\omega_0+\theta(t))\}$, where ω_0 is the optical carrier angular frequency, $\theta(t)$ is the modulating phase corresponding to the payload data, and $P(t)$ is the optical power containing the label information, $P(t)=P_{\max}$ when the label data=1, $P(t)=P_{\max}\cdot(1-m)$ when the label data=0, where m is the modulation depth of the label.

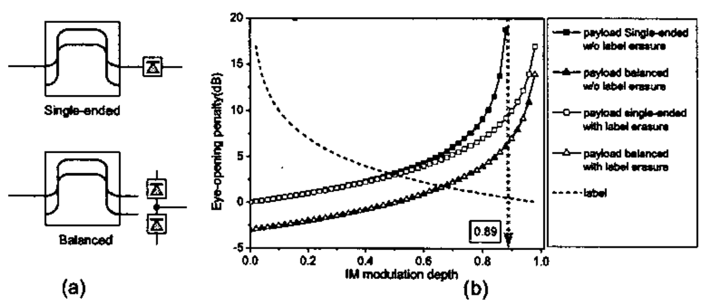

Fig. 1. (a) Two types of DPSK demodulators, (b) theoretical eye-opening penalty vs. Modulation depth for the DPSK payload and IM label.

At the receiver, the label can be detected directly by a photodiode. To recover the DPSK payload, a Mach-Zehnder delay interferometer (MZDI) is used to realize phase to amplitude modulation conversion. Depending on the number of photodetectors, two kinds of DPSK demodulators are considered here, i.e., a single-ended receiver and a balanced receiver, as illustrated in Fig.1(a). If label erasure is not performed before DPSK demodulation, the demodulated DPSK signal presents a multi-level structure due to the intensity fluctuation [3], and the eye-opening A is determined by the difference between the highest level for "0" and the lowest level for "1". The eye-opening penalty (EOP) can be defined as $10\log_{10}(B/A)$, where B is the eye-opening with 0 modulation depth. Then the EOP of the single-ended receiver can be expressed as $10\log_{10}(\frac{4}{2-3m+2\sqrt{1-m}})$, while, for the balanced receiver, the eye-opening penalty is $10\log_{10}(2/(1-m))$. Fig.1(b) shows the EOP for the DPSK payload and IM label as a function of the modulation depth. The EOP of the IM label reduces as the modulation depth is increased, while the EOP of the DPSK payload enhances due to the reduced signal power when an IM '0' is transmitted. Therefore, the modulation depth of the IM label has to be limited. If a single-ended receiver is applied in the DPSK detection, the modulation depth cannot be larger than 0.89.

A packet switched network architecture requires optical labels to be swapped (label erasure and reinsertion) during the routing process. Erasing the label can be easily achieved by passing the DPSK/IM signal through an electro-absorption modulator (EAM), which is driven by the inverted label with appropriate voltage and time delay. In this way, a pure optical DPSK signal is obtained. For simplicity but without losing generality, we neglect the insertion loss of the EAM such that the DPSK payload after label erasure acquires a constant intensity of $P(t) = P_{\max}\cdot(1-m)$. Fig.1(b) also gives the EOP of the label-erased DPSK payload. There is no further penalty caused by label erasure if a balanced receiver is used in the system. For the single-ended receiver, an even lower penalty can be expected when the modulation depth is larger than 0.5.

The DPSK/IM labeling technique has the following advantages: (i) better spectral efficiency compared to the sub-carrier multiplexing and IM/FSK methods, leading to good resilience to fiber chromatic dispersion, (ii) the labeling processing can be kept intact when upgrading the payload speed in contrast to the traditional sub-carrier multiplexing method where it is necessary to change the RF frequency if the payload bit rate is increased, (iii) better tolerance to nonlinear impairments of the high speed payload (≥40 Gbit/s) during transmission, (iv) due to the fact that the relatively lower bit rate label (typically up to a few Gbit/s for compatibility with electronic label processing) is renewed at each node, the modulation depth only needs to be large enough as to ensure the label transmission for just one hop. This small modulation depth can further extend the multi-hop transmission of the DPSK payload, which leads to DPSK/IM labeling having a larger tolerance to the modulation depth than IM/DPSK labeling.

3. Experimental setup and results

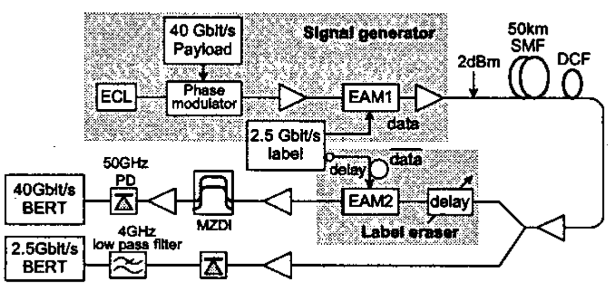

Fig. 2. Experimental setup.

The experimental setup is shown in Fig. 2. The DPSK modulation is generated with a phase modulator driven by a 40 Gbit/s (PRBS 2^{23}-1) NRZ data stream. The pre-coder circuit for the DPSK format is not applied in the experiment because the test signal is a PRBS pattern. The label information at 2.5 Gbit/s (PRBS 2^{7}-1) is added by a following EAM, thus producing an optically DPSK/IM labeled signal. The advantage of using an EAM for label insertion is its negligible frequency chirp, which is extremely desirable in our orthogonal DPSK/IM labeling scheme [6]. The EAMs used in this paper are multiple-quantum-well (MQW) devices, which are 150 μm long and contain 15 quantum wells. The fiber-to-fiber loss at zero bias is about 10 dB. The static transfer curve (transmittance as a function of bias) is a quasi-linear curve up to about -2.5 V with a slope of –9 dB/V.

The transmission span consists of 50 km of standard single mode fiber (SMF) with a matching length of dispersion compensating fiber (DCF) in a post-compensation scheme. The dispersion of the SMF and DCF is 16.9 ps/nm/km and –100 ps/nm/km, respectively.

At the receiver node, the labeled signal is split using a 3 dB optical coupler. The output of one arm is directly detected by a photodiode and thus the optical label is converted into the electrical domain. From the second output of the coupler the labeled signal is launched to another EAM driven by the inverted label data with suitable delay and amplitude for label erasure. The payload is then fed to an integrated MZDI to demodulate the DPSK signal. The length difference between the two arms of the MZDI is 5.049 mm, corresponding to 25 ps delay. The signal at the output of the MZDI is detected by a 50 GHz photodiode and input to a 40 Gbit/s BER test set. Fig. 3(a) shows the BER curves in the back-to-back case and after transmission over 50 km. The inset figures (i) and (ii) show the detected DPSK eye-diagrams without and with label erasure, respectively. Obviously, due to the intensity crosstalk from the IM label, the demodulated DPSK payload eye-diagram presents a multi-level structure before label erasure. After label erasure, a good eye pattern of the demodulated payload is received. The received IM label eye diagrams are shown in Fig. 3(iii). For a pure 40 Gb/s DPSK signal, the transmission penalty is 2.3 dB. For the optically labeled DPSK signal, the labeling causes an additional 5 dB penalty. The transmission penalty for the label is around 2 dB. It is envisaged that better sensitivity performance could be achieved if a balanced-receiver were applied to the payload.

Compared to our previous results on the RZ-DPSK/IM scheme, the labeling penalty for the payload is 2.7dB larger, while the label performance is almost the same no matter which kind of payload is used. Fig.3(b) shows the optical spectra in the DPSK/IM scheme and RZ-DPSK/IM scheme for the labeled payload and the payload after label erasure and demodulation. Although RZ-DPSK/IM labeling shows better receiver sensitivity and smaller labeling penalty for the payload, its optical spectrum is 1.5 times wider than the DPSK/IM labeling, which leads to smaller spectral efficiency in WDM networks. We also compare the optical spectra before and after label encoding and transmission; there is no substantial spectral broadening due to the labeling and transmission.

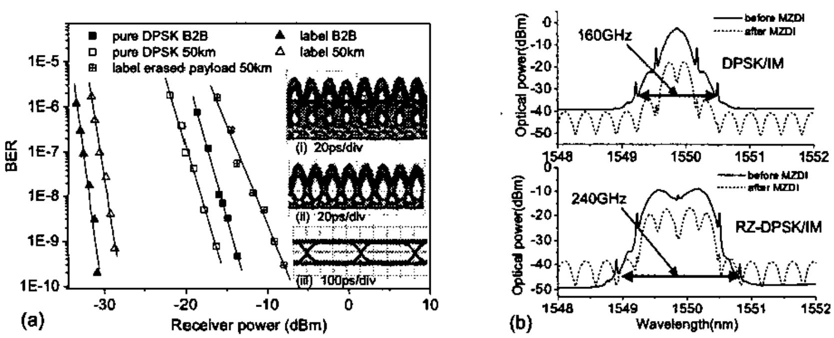

Fig. 3. (a) Measured BER results for the payload and label for DPSK/IM labeling, the inset figures show the eye diagrams for (i) payload without label erasure, (ii) payload with label erasure, (iii) detected label, (b) the optical spectra of the DPSK/IM labeling (above) and RZ-DPSK labeling (below).

4. Conclusion

We have presented our new approach for orthogonal DPSK/IM optical labeling. We have experimentally demonstrated label encoding, transmission over a 50 km SMF link, and label erasure of a 40 Gbit/s DPSK modulated payload using an orthogonal 2.5 Gbit/s IM label. Thus the feasibility of the proposed DPSK/IM orthogonal labeling scheme is clearly validated. This work is performed within the framework of the IST STOLAS (Switching Technologies for Optically Labeled Signals) project.

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